AECD - 2051

UNITED STATES ATOMIC ENERGY COMMISSION

PORTABLE ALPHA-ACTIVITY MEASURING INSTRUMENT

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This document consists of 10 pages.
Date of Manuscript: May 25, 1945
Date Declassified: June 8, 1948

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Technical Information Division, Oak Ridge Directed Operations

AEC, Oak Ridge, Tenn., 9-24-48-1500

Printed in U.S.A.
PRICE 10 CENTS

PORTABLE ALPHA - ACTIVITY MEASURING INSTRUMENT

By C. S. Wu and L. J. Rainwater

INTRODUCTION

A portable sensitive alpha-particle detector has been developed for scanning and surveying small amounts of U-metal on various surfaces. Although there are various possible ways of detecting alpha-particles, for the sake of simplicity and serviceability, the method using an ionization chamber in connection with a portable electrometer circuit is employed. Units built in this laboratory have proven very satisfactory. The high sensitivity that has been achieved with these instruments approximates counter sensitivities. Survey meters type WR-3 based on models described here are being produced by Technical Associates, Inc.

ELECTROMETER CIRCUIT

As it has been pointed out in our report (No. A-3239), a battery-operated inverse feedback electrometer circuit has proven much superior to the ordinary straightforward two-stage DC amplifier (Report A-2131), so the former circuit was finally adopted as the basis for the portable alpha-activity survey

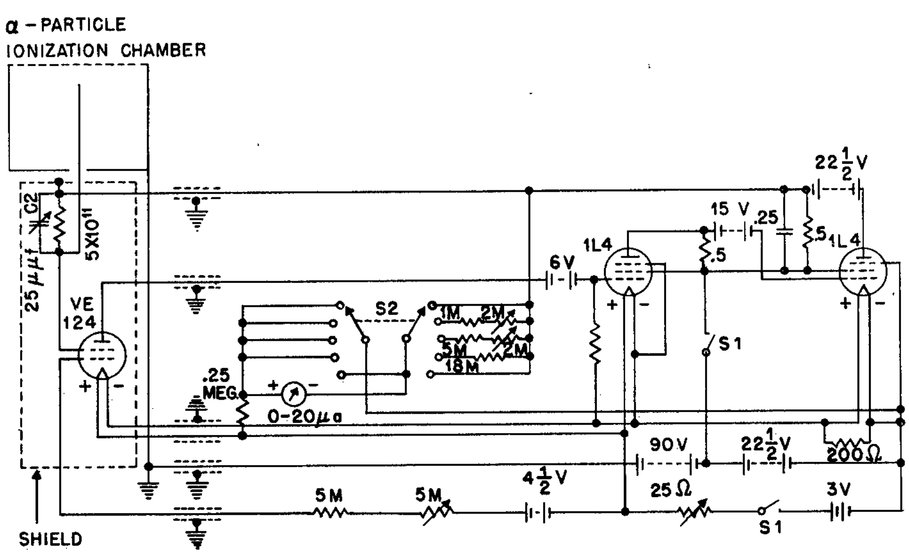

Figure 1. Three stage negative feedback electrometer circuit.

measuring instrument. The circuit diagram is shown in Figure 1. The 0 to 20 microampere output meter has an internal resistance of about 2000 ohms, making the overall voltage sensitivity 40 mv for full scale deflection on the most sensitive range. Less sensitive ranges can be obtained by inserting appropriate resistances in series with the microammeter. In the standard Type WR-3 unit, four ranges of sensitivity of 40, 80, 160, and 400 mv for full scale deflection are provided. This range proves quite adequate in general application. For scanning use, where a quick response is highly desirable, the small variable condenser C_2, which is usually provided between the input grid and feedback point for the regulation of time constant, is omitted to give as short a time constant as possible. Owing to the special shielding arrangement of the input circuit in this unit, the distributed feedback capacitance is quite considerable. When a 5 x 10^{11} ohms resistor is used as input impedance, the time constant is around 3 seconds with the feedback capacitance adjusted to a minimum.

CONSTRUCTION

The layout of the alpha-activity measuring instrument normally employed is in two parts. The ionization chamber together with the input stage form a probe device similar in size and shape to an ordinary flashlight. The other two stages, the microammeter, and the batteries are housed in a separate metal box to form the other part of the unit. A ten-foot shielded cable connecting them gives an ample degree of freedom to the ionization chamber while the main instrument box is securely resting nearby.

IONIZATION CHAMBER

Since the input circuit and the collector electrode are mounted in the handle part of the probe and operate at a high negative potential relative to the outside case, which is grounded, it is possible to make use of this grounded outside case as an ionization chamber which consists of a simple metal cap with a screen opening at the end or on the side to define the chamber volume and chamber opening. For this reason different chambers can be rapidly attached to the basic probe handle. In particular a tubular chamber with the screen on the side permits measurements to be made inside pipes or similar objects.

The shape and size of the ionization chamber depends entirely on its application. For general use a cylindrical shaped chamber of a diameter 2.5 inches and depth 1 1/4 inches is quite suitable. The front window where the alpha particles enter into the chamber is normally made of wire mesh. In deciding the optimum size of the mesh, two factors should be taken into consideration, (a) the transparency to the alpha particles and (b) the screening to the electrostatic effects.

Theoretical calculations show that the transparency to alpha particles mainly depends on the ratio of the diameter of the individual wires to the spacing between them (see Figure 5), but the screening effect for the electrostatic disturbance is largely determined by the spacing between the wires where the size of the wire is small compared to the spacing. Therefore, the optimum mesh would be the one which consists of extremely thin wire interwoven into a mesh which has a spacing about five times the size of the wire. There is no wire screening on the market which answers this criterion so far as we know. The nearest commercially available product is 100-mesh copper screening. This is then etched with nitric acid until the individual wires have been reduced to about 0.002 inch diameter. This mesh still has sufficient mechanical strength and the transparency to alpha particles is around 50%. (This gives a transparency about three times that for the untreated screen.) The electrostatic screening is very satisfactory.

The input tube VE124, high resistance and the supported end of the central collecting rod are rigidly mounted within and completely shielded by a brass tubing of 1 3/8 inches diameter. This shielding tube is then directly connected to the feedback point and shock-proof mounted to the outside case which has a diameter of 1 5/8 inches. With this special precaution in shielding, the stability of the meter with respect to the turning or jarring of the outside case of the input circuit improves a great deal. Only by

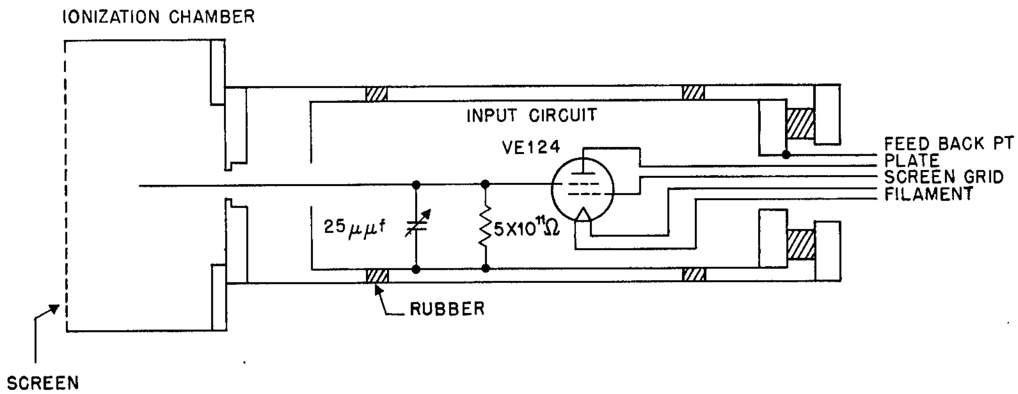

Figure 2. Head probe of the alpha-particle measuring instrument.

swinging the outside case violently through a considerable angle does the needle of the meter wave a few divisions. The detail drawing of the probe part is shown in Figure 2. The photograph of the complete unit is shown in Figure 3.

RESULTS

With the size of the ionization chamber mentioned above (diameter 2 1/2 inches, depth 1 1/4 inches) and an input resistance of 5 x 10^{11} ohms, 0.30 mg of normal U-oxide gives one quarter of full scale deflection on the most sensitive range. It is rather easy to detect 0.10 mg of normal U-oxide. Since 0.30 mg of normal U-oxide emits only three alpha particles per second in the upward 2 π solid angle, the number of alpha particles which get into the chamber can hardly be more than half of this value or 1.5 alpha/second. Because of the random emission of alpha particles from any radioactive source, the only limitations on further extending the sensitivity of this type of instrument are the statistical fluctuations. Even in the present unit, the individual alpha-kicks are easily observable and statistical fluctuations make the taking of a reading very difficult. However, if the time constant does not have to be short, the effect of the statistical fluctuations can be decreased considerably by increasing C_2 which is in parallel with the high resistor. This is discussed in detail in the appendix.

VE32 BALANCED CIRCUIT WITH POSITIVE FEEDBACK

During the development of the alpha-activity measuring instrument, a sensitive and stable DC amplifier circuit employing two type VE32 tubes has also been designed and tested. The circuit is shown in Figure 4. The two VE32 tubes are connected in push-pull "ring" fashion. The effects on the output current due to any changes in filament current or plate voltage are balanced out and therefore it has very good stability. A two tube balanced circuit without positive feedback from the plate of the second tube to the grid of the first tube gives a sensitivity of about 0.08 microamp/millivolt which is not sensitive enough for certain purposes. By introducing positive feedback, the sensitivity can be gradually varied by controlling the amount of feedback up to the point of oscillation. However, it has been found that a factor of five or six times the sensitivity can be obtained without unduly impeding the stability of the circuit. The linearity cannot be expected to be too satisfactory on account of the characteristics of positive feedback, but if the input voltage range can be limited to a small value the nonlinearity is not at all

Figure 3. Alpha-particle measuring instrument.

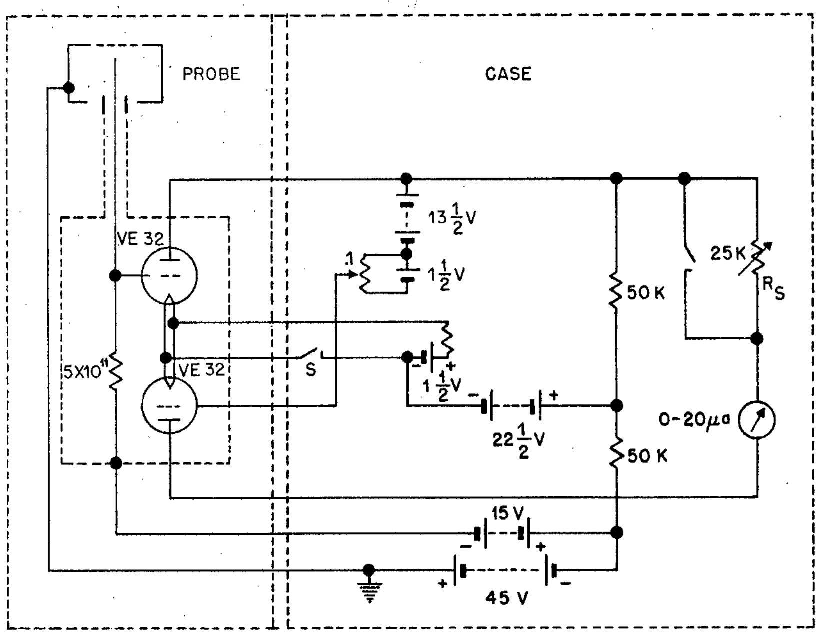

Figure 4. VE32. Circuit with positive feedback.

serious. The unit completed in this laboratory has a sensitivity almost as good as the one with the three stage negative feedback circuit. The disadvantages of this circuit relative to the three tube inverse feedback circuit are (a) it is not perfectly linear, (b) the sensitivity is not strictly constant, (c) the minimum time constant is larger (this is not always undesirable). The outstanding features of compactness and simplicity possessed by this circuit are highly desirable in certain cases.

INPUT TIME CONSTANT OF CIRCUITS

For a conventional electrometer circuit the input circuit is as shown in Figure 6a. R is the input resistance used, which may be as large as 10^{12} ohms, and C is the total capacity to ground of the input circuit including the chamber, the leads and the input grid. C will normally be of the order of 10 to 30 $\mu\mu$f and, with $R = 10^{12}$ ohms, will give a time constant $\tau = RC = 10$ to 30 seconds. For an inverse feedback amplifier as shown in Figure 6b most of the change in voltage ($\Delta E_1 - \Delta E_2$) across the input resistance R takes place at the feedback end rather than at the grid end. The ratio $(\Delta E_1 - \Delta E_2)/\Delta E_1$ represents the feedback factor, K_1, of the circuit and gives the ratio of circuit sensitivity with feedback removed to that with feedback employed. In Figure 6b the capacity C_1 to ground represents the sum of the chamber capacity and the tube and lead capacities. The capacitance C_2 is introduced in parallel with R to improve the stability of the circuit and to regulate the time constant. For Figure 6b the effective time constant $\tau = [RC_2 + RC_1/K_1]$. If C_1/K_1 is small compared to C_2 (large feedback factor), the value of the time constant is effectively $\tau = RC_2$. (In order to have proper circuit stability, the value of C_2 should not be small compared to C_1/K_1.) For the particular condition $C_2 = C_1/K_1$, it is seen that the time constant of the inverse feedback circuit is reduced by a factor of $K_1/2$ relative to that of Figure 6a. The value of C_1 may be reduced by transferring the distributed capacitance of the input leads to C_2 by enclosing the tube and input leads in a separate shielded container connected to the feedback point.

The circuit of Figure 6c is typical of circuits using positive feedback to the input. The change in voltage ($\Delta E_1 - \Delta E_2$) across the input resistor R is less than the change at the input grid ΔE_1. The positive feedback factor $K_1 = \Delta E_1/(\Delta E_1 - \Delta E_2)$ gives the ratio of sensitivity with feedback to that without feedback. The capacity C and the resistance R have the same significance as for Figure 6a. The effective time constant for Figure 6c is $\tau = K_1RC$ which is the same as for Figure 6a times the feedback factor. If RC = 20 sec and $K_1 = 10$, this is seen to increase the time constant to 200 sec which is usually too large.

When the time constants of Figures 6a, 6b, 6c are larger than desired it is possible artificially to decrease them by employing positive capacity feedback as shown in Figures 6d, 6e, 6f. The feedback capacitance may be obtained by adding a small capacitor or, more conveniently, by utilizing the chamber capacitance. To do this the chamber collecting voltage batteries are connected to a point in the plate

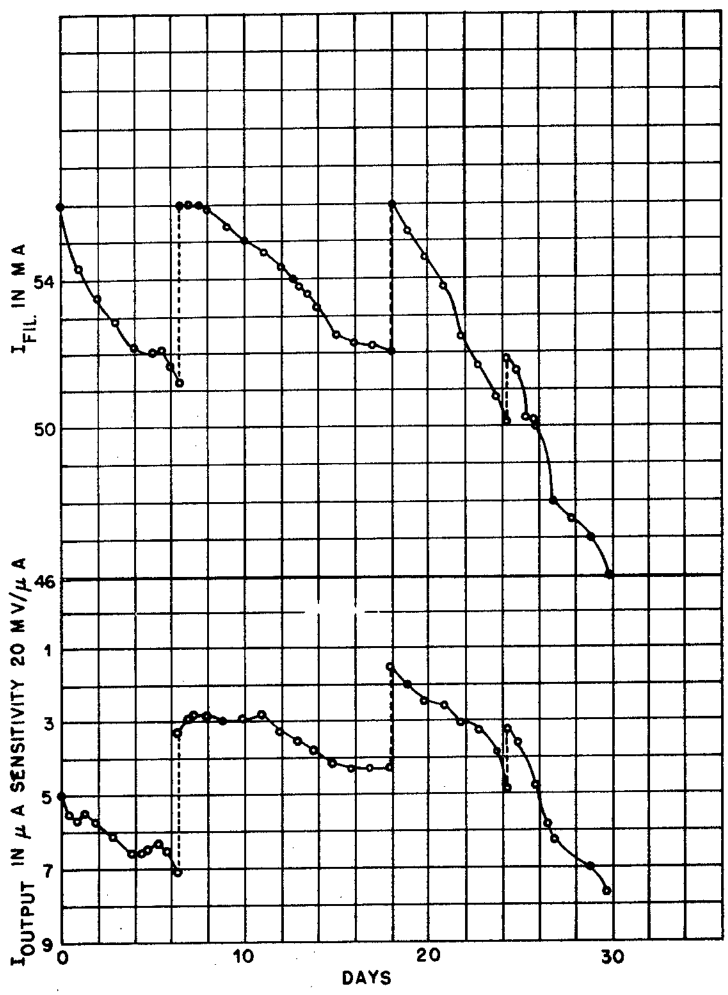

Figure 5. Battery life test. Tubes not previously aged and temperature not held constant.

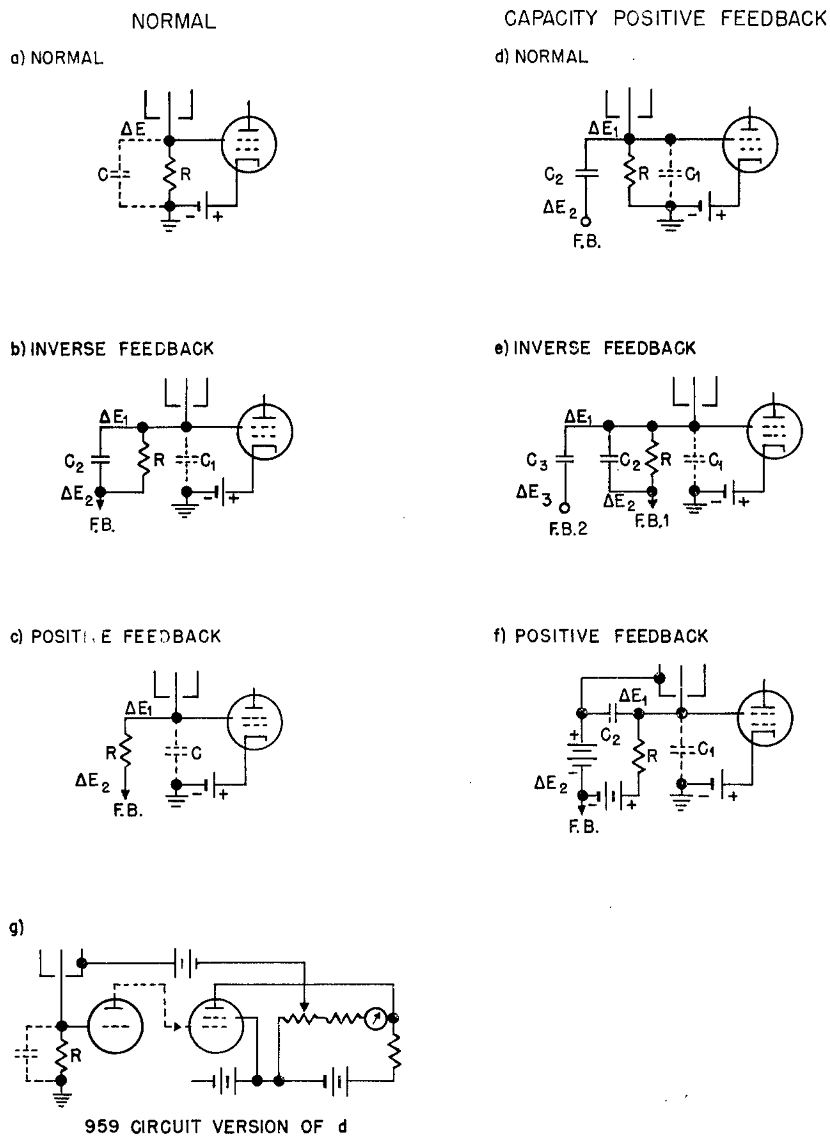
NORMAL
CAPACITY POSITIVE FEEDBACK
a) NORMAL
ΔE
C
R
d) NORMAL
ΔE1
C2
R
C1
ΔE2
F.B.
b) INVERSE FEEDBACK
ΔE1
C2
R
C1
ΔE2
F.B.
e) INVERSE FEEDBACK
ΔE1
C3
C2
R
C1
ΔE3
ΔE2
F.B.2
F.B.1
c) POSITIVE FEEDBACK
ΔE1
R
C
ΔE2
F.B.
f) POSITIVE FEEDBACK
ΔE1
C2
R
C1
ΔE2
F.B.
g)
R
959 CIRCUIT VERSION OF d

Figure 6.

circuit of the second tube so the chamber voltage will change in the same direction as the grid voltage. If the two change by equal amounts, the effect of the chamber capacity is cancelled. If the chamber voltage changes faster than the input voltage, the chamber capacity plus part or all of the lead and tube capacity may be cancelled, or it may be increased to the point of oscillation. The effective time constant in Figure 6d is $\tau = R[(C_1 + C_2) - K_2C_2]$ where $K_2 = \Delta E_2/\Delta E_1$ is the feedback voltage ratio. The critical value for oscillation is $K_2 = (C_1 + C_2)/C_2$.

The circuit of Figure 6d has been tried using the two tube 959 circuit described in report A-2131 by the modification shown in Figure 6g. When the unmodified circuit was used for the detection of alpha rays with a 10^{12} ohm input resistance, the time constant RC was about 25 seconds. By increasing K_2 to near oscillation it was possible to reduce τ to such a small value that the individual alpha kicks were an appreciable fraction of full scale. The individual alpha particles could then be counted with some accuracy by counting the meter kicks. When the time constant of the circuit is reduced so much with such high sensitivity, however, it loses its significance as a "rate-meter" circuit (see the appendix). The meter reading then is normally zero until a particle is detected to give a brief kick of several divisions.

The circuit in Figure 6e has not been tested because the inverse feedback principle allows a satisfactory reduction in time constant alone. It has been included for completeness. If $K_2 = \Delta E_3/\Delta E_1$ and $K_1 = (\Delta E_1 - \Delta E_2)/\Delta E_1$, then the effective time constant is $\tau = R[C_2 + (C_1 + C_3 - K_2C_3)/K_1]$ and the critical value for K_2 is $K_2 = (C_1 + C_3 + K_1C_2)/C_3$. It should be noted that ΔE_3 is opposite in direction to ΔE_2.

The circuit of Figure 6f has been used with the two tube V-32 positive feedback circuit by connecting the collecting voltage battery to the plate of the second tube and by mounting the tube and input leads in a separate shielded box connected to the feedback point. In this way $K_2 = \Delta E_2/\Delta E_1 < 1$ and $K_1 = \Delta E_1(\Delta E_1 - \Delta E_2)$ as before. The time constant $\tau = K_1R(C_1 + C_2 - K_2C_2)$. This circuit was tried but not used as the longer time constant was desired at that time to give a more stable reading (see appendix).

In using the circuits of Figures 6d, 6e, 6f, 6g it should be mentioned that the basic time constant of the circuit for recovery from any disturbance (zero adjusting, etc.) other than an input signal is still associated with a longer time constant related to a different ratio of voltage change at the different points.

APPENDIX

STATISTICAL CONSIDERATIONS

The sensitivity of the instrument described in this paper has been improved to such a degree that even an alpha-particle source emitting an average of only (1–2) alpha particles per second which enter the chamber gives an appreciable deflection on the output meter. In other words, the instrument has attained the sensitivity of a counter system in which the single elementary processes are observed. The general considerations concerning the counting time required for a given accuracy should therefore be applied to the readings of this instrument. However, it is very easy for one to overlook the magnitude of these factors and therefore fail to realize the incompatibility between having a short time response of the instrument and a high degree of constancy for the readings. A detailed discussion of these factors is included here.

If n random events are detected per unit time (averaged over a very large time) when measuring a a radioactive source of constant (long half-life) intensity, the count obtained by counting for a time t will be expected to differ from $N = nt$, the average of many such measurements, by some amount. This deviation may be large or small and positive or negative. The absolute magnitude of the deviations obtained from several such measurements will be of the order of the magnitude of the square root of the value, or $\sqrt{N}$, on the average. This corresponds to a fractional uncertainty in a single measurement of the order of $1/\sqrt{N}$.

From this the approximate number of counts required to limit the statistical uncertainty to a certain value may be computed. In the Table 1 the percentage statistical uncertainty is given in the first column and the number of counts N = nt required for this accuracy in the second column. The third column gives the time in seconds required when the average ratio is 1.5/second (approximately the rate for the measurement of 0.3 mg of normal U-oxide.

Table 1. Basic limitations due only to statistical considerations.

			Time to reach x% of equilbrium			
% uncertainty	N = nt	t if n = 1.5/sec	80%	95%	99%	99.9%
20	25	17 s	27 s	51 s	78 s	117 s
10	100	67 s	104 s	200 s	5.1 m	7.7 m
5	400	267 s	430 s	13.3 m	20.6 m	30.9 m
2	2,500	27.8 m	45 m	83 m	128 m	192 m
1	10,000	111 m	3 h	5.6 h	8.5 h	12.8 h
0.1	10^6	7.7 d	12.4 d	23 d	35.4 d	53 d

When a circuit is used which gives a reading proportional to the rate of occurrence of events as is true with these circuits or of a Geiger counter ratemeter circuit, there is usually a single or main time constant of response, τ, in the circuit that determines the time required for the circuit to reach equilibrium when the rate is changed. The law followed by the response is then as follows: a given deflection is caused by particles arriving at a constant rate R_1 (no statistical fluctuations) after a sufficient time has elapsed for the circuit to reach equilibrium. If at a certain time, t = 0, the rate is suddenly changed to R_2 the apparent rate, $R_m(t)$, as indicated by the meter at a time t later will be $R_m(t) = [R_2 - (R_2 - R_1)e^{-t/\tau}]$. The time required to reach 90% of equilibrium is thus $t = 2.3\tau$ and to reach 99% of equilibrium is $t = 4.6\tau$.

When the rate of occurrence is continuously varying R = R(t) at a time t, then the rate indicated by the meter at the time t will be

$$R_m(t) = \int_{-\infty}^{t} R(\lambda) e^{-\frac{(t-\lambda)}{\tau}} \, d\lambda.$$

This averages the rate over all past time but weights events $(t - \lambda)$ distant in the past less by the factor $e^{-(t-\lambda)/\tau}$. In this case the time to reach near equilibrium when a different source strength is observed is the same as for constant rates by the significance is different. In this case the circuit is said to have reached 90% of equilibrium for the measurement of a new sample if the reading gives a 90% weighting to events which occurred after the sample was changed and 10% to events before that time. In this manner there is significance to the statement that the circuit has had time enough to reach 99% of equilibrium even though the statistical fluctuations in the rate from the source may cause the reading to fluctuate with an amplitude of 20% about its mean value.

When a "ratemeter" circuit is used to detect random events the magnitude of the fluctuations in the readings about the mean will be the same size as for individual counts taken over a period of time equal to the time constant of response of the circuit, τ. The third column in the table thus also corresponds to the time constant required for a given statistical accuracy of direct reading at a rate of 1.5/second. The last four columns give the time required for the circuit to reach 80, 95, 99, and 99.9% of equilibrium as defined above.

From Table 1 it is seen that a 17-second time constant is required for 20% uncertainty and 51 seconds to reach 95% of equilibrium. For a 5% uncertainty and to reach 99% of equilibrium requires 20.6 minutes while to obtain 1% requires many hours and 0.1% several months.

For scanning purposes it is often desirable to have a short time constant for a rapid response. In one model of this instrument a time constant of about 3 seconds was used with the advantage that 99% of equilibrium is reached in 14 seconds. For a rate of 1.5/second circuit averages over 4.5 events on the average. This corresponds to a fluctuation in reading of the same order as the magnitude of the average reading, but it is possible to obtain only 20% uncertainty in a reading by waiting 15 seconds and then watching the meter for the next 30 seconds to average the reading mentally. For higher accuracy at such slow rates the time constant should be increased and a similar technique used over a longer time as indicated in Table 1.

It is of interest to notice that if n/second produces 1 division deflection and the time constant is τ, then the average deflection produced by one particle is $(1)/(n\tau)$ while those having almost full range in the chamber may produce almost twice this deflection. If $(1/n) = 7$ and $\tau = 3$ seconds, the average meter kick per particle is 2.3 divisions which is easily observed by watching the meter. It is even possible with some accuracy to count the individual particles in this manner. With the inverse feedback circuit the time constant can be reduced still more to give 4 to 5 division kicks for each particle. The circuit then becomes less of a "ratemeter" device than a "counting" device as the circuit tends to recover to zero between particles.

It should be emphasized that the factors presented in this appendix are fundamental in nature and not just the limitations of any particular measuring device.